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DEVELOPMENT OF A HIGH SPEED DIGITAL RECORDING SYSTEM

Report No. 86-112-K

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ABSTRACT

The increasing use of vacuum switchgear for controlling large AC motors has raised concerns that voltage surges created during circuit breaker switching operations may damage the turn insulation of motor coils. In order to examine the threat posed by these surges to a motors turn insulation, EPRI initiated project RP2307-1 "Turn Insulation Capability of Large AC Motors". As part of this project it was necessary to design a very high bandwidth, 3 channel digital recording system to monitor switching surges on motor's controlled by vacuum circuit breakers. This state-of-the-art computer controlled monitoring system is capable of taking an 8-bit sample every 5 ns and is used to make unattended measurements of high speed voltage transients appearing at the motor terminals. The system has been successfully used to monitor surges on a number of 4.1 kV induction motors controlled by vacuum circuit breakers. With minor modifications, it could be adapted for use in other applications where accurate measurement of fast risetime voltage transients is required.

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To Mr. F.J. Kee
Director of Research

DEVELOPMENT OF A HIGH SPEED DIGITAL RECORDING SYSTEM

B.A. Lloyd and S.R. Campbell

INTRODUCTION

As part of EPRI project RP2307-1 "Turn Insulation Capabilities of Large AC Motors", two automatic measurement systems were developed to monitor voltage surges impinging on motor terminals during circuit breaker switching operations [1]. Although these systems are adequate for measuring voltage surges on motors switched by air magnetic breakers, a more sophisticated instrument is required where vacuum breakers are used. Tests have shown that multiple transients with very fast risetimes are created by switching of vacuum circuit breakers [2]. To accurately measure the magnitude of these surges, a system with very high bandwidth is required. This report describes a state-of-the-art three channel digital recording system that has been developed for automatically monitoring switching surges on 4 kV motors. This computer-controlled system is based on three of the fastest digitizers commercially available. In order to properly measure the large number of transients that can be present during one switching operation, a custom ECL trigger and timing circuit is used to control the digitizers' sampling. By altering the existing controlling software and hardware, it may be possible to use this system for monitoring fast voltage transients in other applications.

SURGE RECORDING SYSTEM

System Specifications:

Many of the requirements in the specification for this measurement system are similar to those for the systems developed earlier to be used on motors switched by air magnetic circuit breakers [1]. Additional constraints were needed to take into account the different characteristics of the surges created by vacuum contactors and their effect on the data acquisition system. As a vacuum breaker closes, a large number of pre-strikes can occur

across the contacts before they meet. This can lead to multiple transients at the motor terminals. These surges are typically much faster and more numerous in the case of motors switched by vacuum circuit breakers than for the case involving switching motors using conventional air magnetic contactors. The following guidelines were used for developing this system:

1. The recording system must be fully automatic and require no operator intervention once it is installed at the motor site. Since circuit breaker operations can occur at any time, it is impractical to have an operator present to interact with the measurement equipment.

2. The order of breaker pole closing can be important to the magnitude and risetimes of the resulting transients [3]. Therefore the system must have three channels so that information from all three phases of the motor can be recorded simultaneously.

3. In preliminary tests at Pickering NGS [2] it was found that surges with risetimes as short as 25 ns could be present on motors switched by vacuum breakers. Therefore the frequency response of the system including the voltage dividers, must be flat from 60 Hz up to 10 MHz, corresponding to a 25 ns risetime.

4. Multiple pre-strikes, separated in time by several tens of microseconds, may occur across each breaker pole as it closes. These pre-strikes can result in multiple, fast risetime surges at the motor terminals. The surge monitoring system must therefore be capable of multiple triggers on each channel.

5. Because of mechanical or electrical variability in the three poles of the circuit breaker, the time difference between pole closings may be in the order of several hundreds of microseconds. Once triggered, the system should record for a long enough period to collect switching data from all three phases. Recording of part of the 60 Hz waveform is also desirable so that the phase angle at which each pole closed can be determined.

6. Depending on the phase angle of the supply voltage when the breaker contacts close, both positive and negative polarity surges may be present. Therefore the system must be able to trigger on either polarity surge.

7. The installation of the measurement system should be straightforward and should not require an unreasonably long outage for the motor.

8. The surge recording equipment should withstand impulses with magnitudes up to 10 pu (34 kV) as well as the normal line to ground 60 Hz stress.

9. Because the magnetic field transient caused by a high current surge at motor turn-on, can interfere with the normal operation of the surge monitoring equipment. The equipment should therefore be contained in an electromagnetically shielded enclosure. This enclosure should also provide adequate protection from dirt and other airborne contaminants.

System Description:

A block diagram of the major components of the surge monitoring system is given in Figure 1. The system is based on three 200 Mhz digitizers (Lecroy model TR8828B). Each of the three digitizers is capable of sampling a voltage waveform every 5 ns and can store up to 64K samples (which corresponds to a minimum time period of 327 μs). The digital data are then transferred to a Compaq portable computer where it is temporarily stored on fixed disk.

Voltage surges are detected by high voltage probes (Tektronix model P6015) connected directly to the three phase terminals of the motor. These probes are rated to safely withstand 40 kV impulses and provide a division ratio of 1000:1. A further division by 8 is accomplished with a resistive voltage divider and a splitter located in the input circuit shown in Figure 1. Since the input voltage for the digital oscilloscope is ± 2.5 V, the overall dynamic range of the system is limited to ± 20 kV or ±6 pu for a 4.1 kV motor.

The trigger and timing circuit shown in the block diagram (Figure 2) was designed to tailor the digitizers' characteristics for this particular application. A common 200 MHz sampling clock is used to synchronize the three digitizers and the trigger and timing circuit. A surge of either polarity, that is larger than a preset threshold level, can initiate a recording. Once triggered, the digitizers begin sampling at a rate of one sample every 5 ns for a count of 256 samples. This "fast" recording is 1.28 μs long which provides adequate detail of a steep fronted transient. The trigger circuit is then rearmed so that further surges can initiate another "fast" recording. After each "fast" recording the timing circuit "slows" the digitizer so that it is effectively sampling every 1.28 μs. If another transient is detected, the digitizer will again switch into the "fast" sampling mode. By varying the sampling rate of the digitizers when no fast transients are present, a longer period can be recorded. This scheme allows up to 256 pre-strikes to be recorded in "fast" mode before the digitizers' memory is exhausted.

A Compaq Plus portable computer is used to store the recorded waveforms and to control the digitizers and the triggering and timing circuits. Communications between the computer and the digitizer crate is over an IEEE-488 interface. The crate has its own Camac protocol that is used to send messages to the digitizers as well as the triggering and timing circuits. The trigger and timing circuits respond to a limited subset of the available Camac commands.

As shown in Figure 1 the computer and digitizers are contained in an electromagnetically shielded container. Four fans are mounted on the back of the enclosure to provide cooling for the system. A photograph of the system being installed on a coal crusher motor is shown in Figure 3.

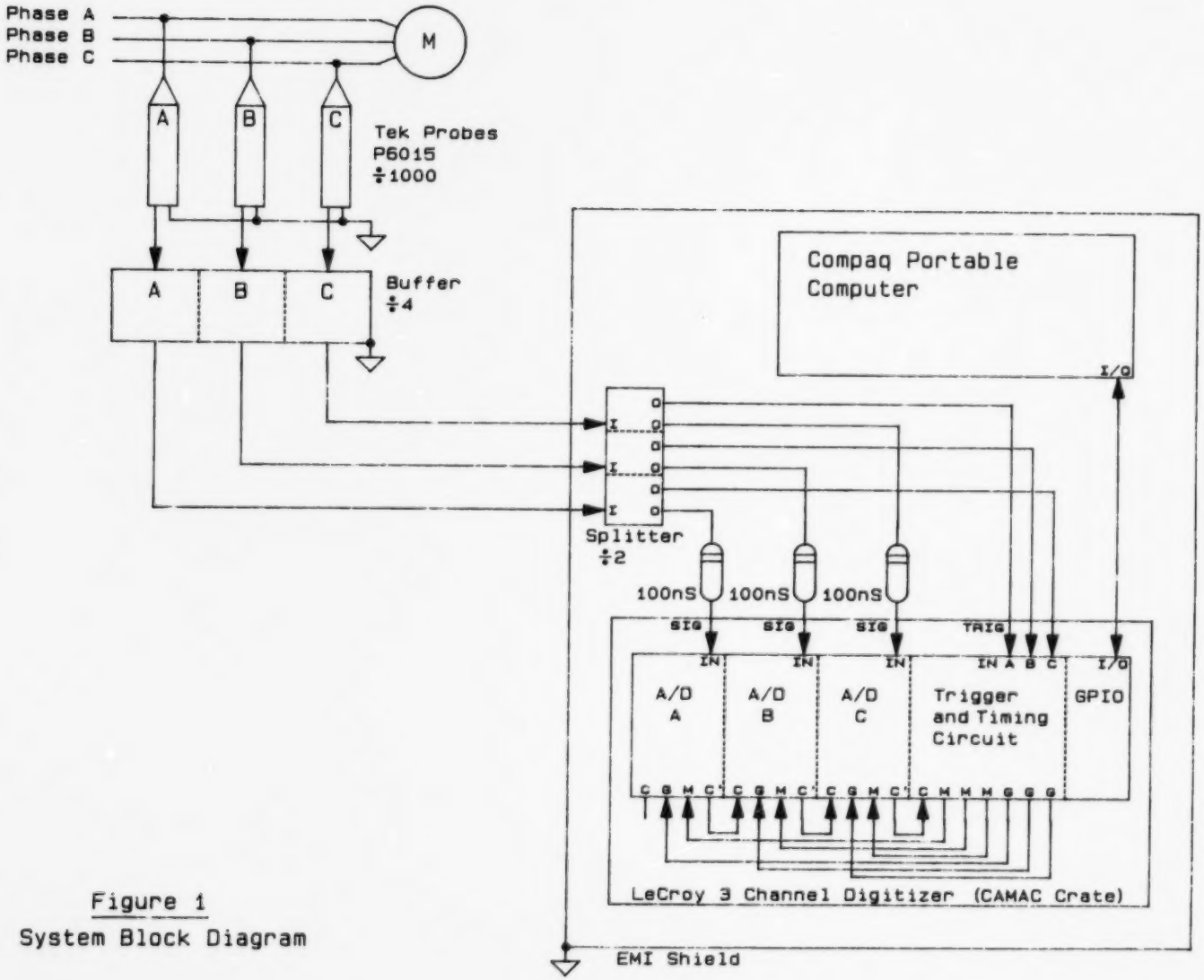

Figure 1
System Block Diagram

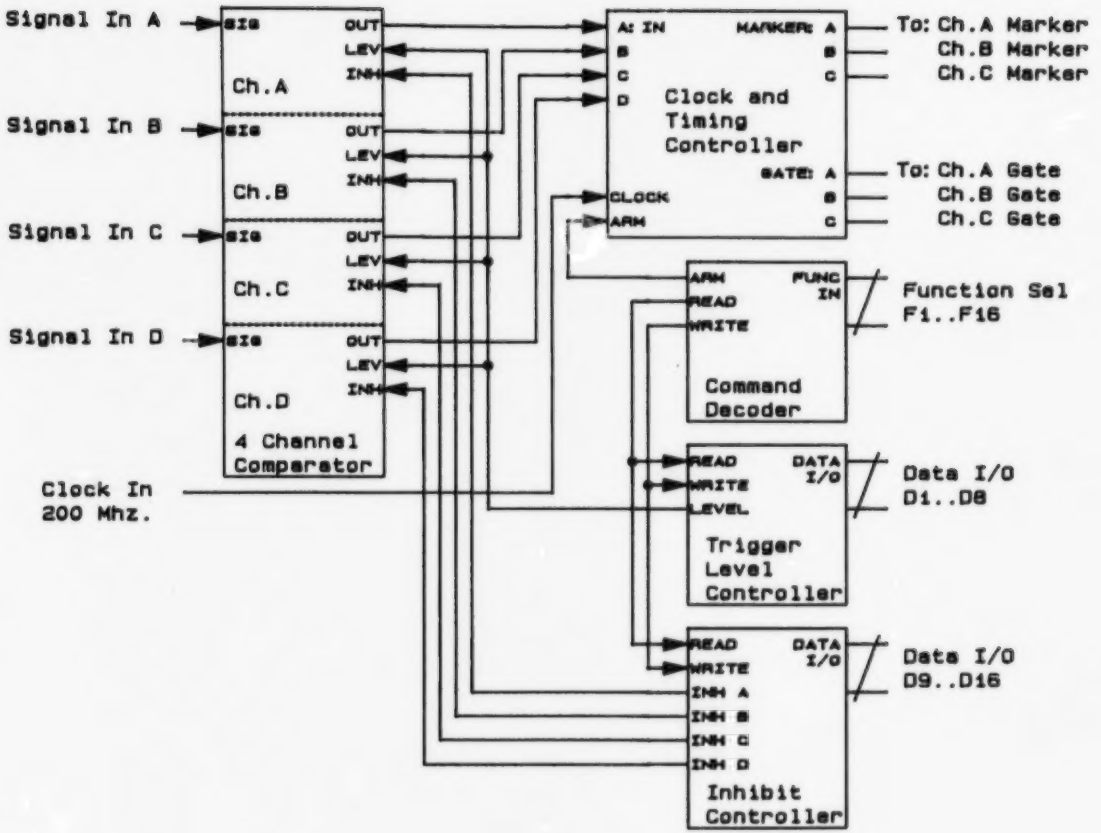

Figure 2

Trigger and Timing Controller
Circuit Block Diagram

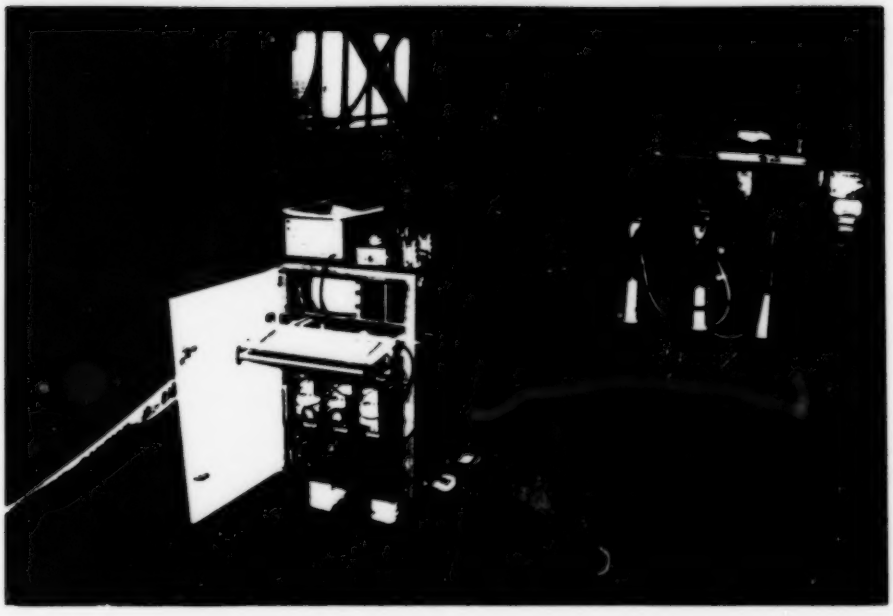

FIGURE 3
The monitoring system being installed on a coal crusher motor
(Cinncinati Gas & Electric, Situation 29, January 1986)
(Safety barriers were removed in order to facilitate taking this photograph)

A typical recording (Figure 4) contains over 100 pre-strikes on each channel. The recording system was triggered initially by a transient on channel B. In order to properly view the recorded data, it is necessary to display each transient separately. The record shown (Figure 4), is a plot of every 100th data point and is therefore not useful for data analysis. The data acquisition and analysis software running on the Compaq portable computer can be used to display all the data points for each "fast" recording. Even though the breaker pole closings are significantly staggered, enough of the 60 Hz waveform is recorded in "slow" mode to determine the point-on-wave where each pole has closed. The recording system has been successfully used to monitor surges in 5 situations to date.

Details on the hardware used in the surge recording system are given in Appendix 1. Details on the IBM compatible software used for data collection and analysis are contained in Appendices 2, 3, 4 and 5.

CONCLUSIONS

A state-of-the-art surge recording system has been built which automatically records any surges appearing at a motor's terminals. The system has been effectively used in a number of situations on motors switched by both air magnetic and vacuum circuit breakers. Given the extremely adverse environment in which it is being used, and the sophistication of the system, it's reliability and ruggedness have proven phenomenal.

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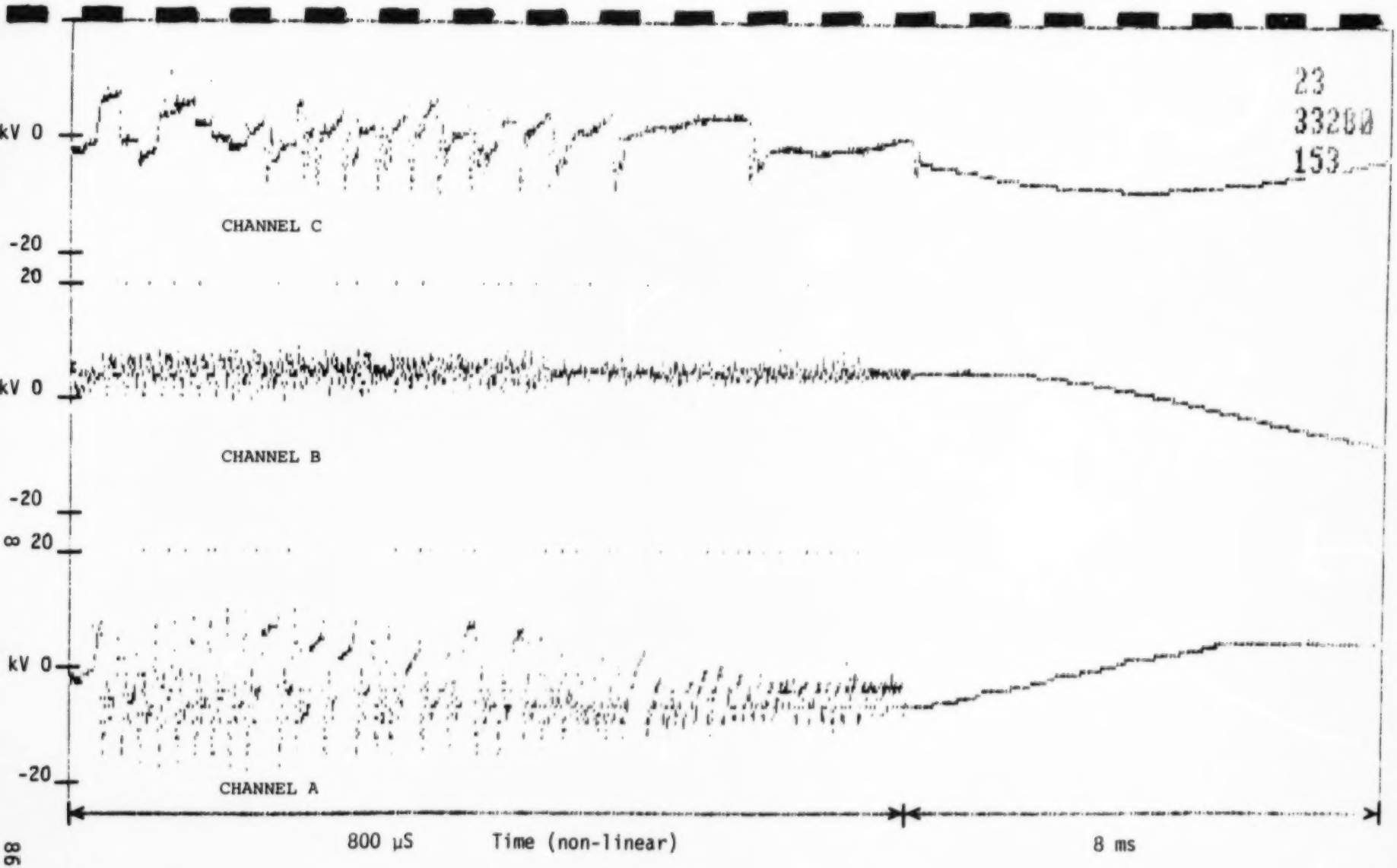

Figure 4

Recording from Situation 29,
Cinncinati Gas and Electric
(January 1976)

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5. Lecroy model 1434 high power Camac crate, LeCroy Research Systems Ltd., March 1984.

6. Lecroy Camac to GPIB Interface, LeCroy Research Systems Ltd., November 1982.

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APPENDIX 1

Hardware Description

Appendix 1

Hardware Description of a High Speed Digital Recording System

The surge monitoring system is built around three Lecroy high speed analogue to digital convertors (Figure 1). Each digitizer is capable of taking an 8 bit sample every 5 ns. A maximum of 64 K discrete samples can be recorded per channel. A trigger and timing controller was designed to detect valid trigger events and control the sampling rate of the digitizers. Voltage surges at the motor terminals are detected via Tektronix high voltage probes. The attenuated signal is then passed through a buffer and fed to the three digitizers. A Compaq portable computer is used to control the trigger and timing circuitry and to store and display the recorded signals.

Three Tektronix P6015 probes are used to detect the motor voltage surges. The probes provide a 1000:1 division ratio and are rated to withstand 20 kv RMS and 40 kv impulses. The input impedance of the probes is 100 MΩ and 3 pF. A 2 m cable connects the probes to a custom made buffer which provides three high impedance inputs and a 4:1 division ratio. The buffer outputs drive 50 Ω coaxial cables which are connected to a resistive matched 50 Ω splitter (2:1 division ratio). The splitter allows the signal to be coupled to the trigger circuit via a short length of cable and to the digitizers via a longer cable. This arrangement causes a delay in the signal to the digitzers and an effective pretrigger of 100 ns for a difference in cable length of 30 m. With an overall division ratio of 8000:1, the system is capable of recording surges with magnitudes up to ±20 kV. In laboratory tests, the system has been proven for risetimes as short as 20 nS although the magnitude accuracy is somewhat reduced.

Three high speed digitizers (LeCroy model TR8825B) are used to record the voltage signal. These digitizers can take an 8 bit sample at a maximum sampling frequency of 200 MHz. Up to 64 K samples can be recorded by each digitizer for each event. The digitizers have the ability to record in a burst mode, with bursts as small as one sample. In the burst mode, the digitized data may or may not be written to memory depending on the signal level on the gate input. By using this burst mode feature, the effective digitizer sampling rate can be changed during a recording. When a transient occurs, the gate is enabled and sampling is done at 5 ns intervals. After a preset time (256 samples) the gate is dropped and is then pulsed only once every 1.28 μs. This gives an effective "slow" sampling rate of 1 sample every 1.28 μs. If another transient is detected, the trigger circuit will again gate the digitizers for a fast recording of 256 samples. This method provides high resolution recording for each transient and a low resolution recording of the entire event in time. In order to provide a marker so that time base information can be recovered from the data, the digitizer inputs are temporarily driven offscale at the end of each high speed recording. The Trigger and Timing Controller can trigger on a fast transient of either polarity on any of the 3 channels. Signals are sensed by the Four Channel Comparator shown in Figure 2.

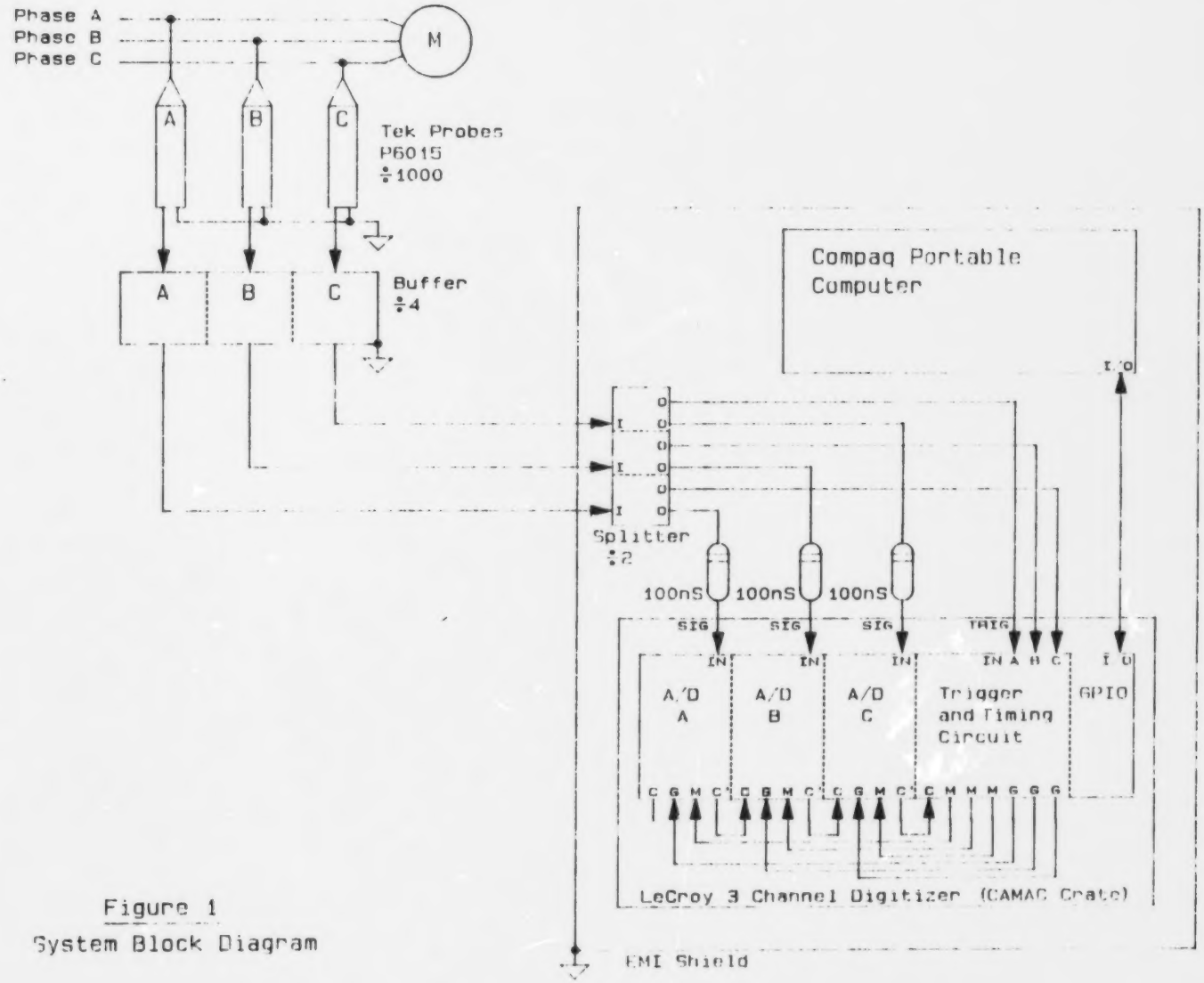


Figure 1
System Block Diagram

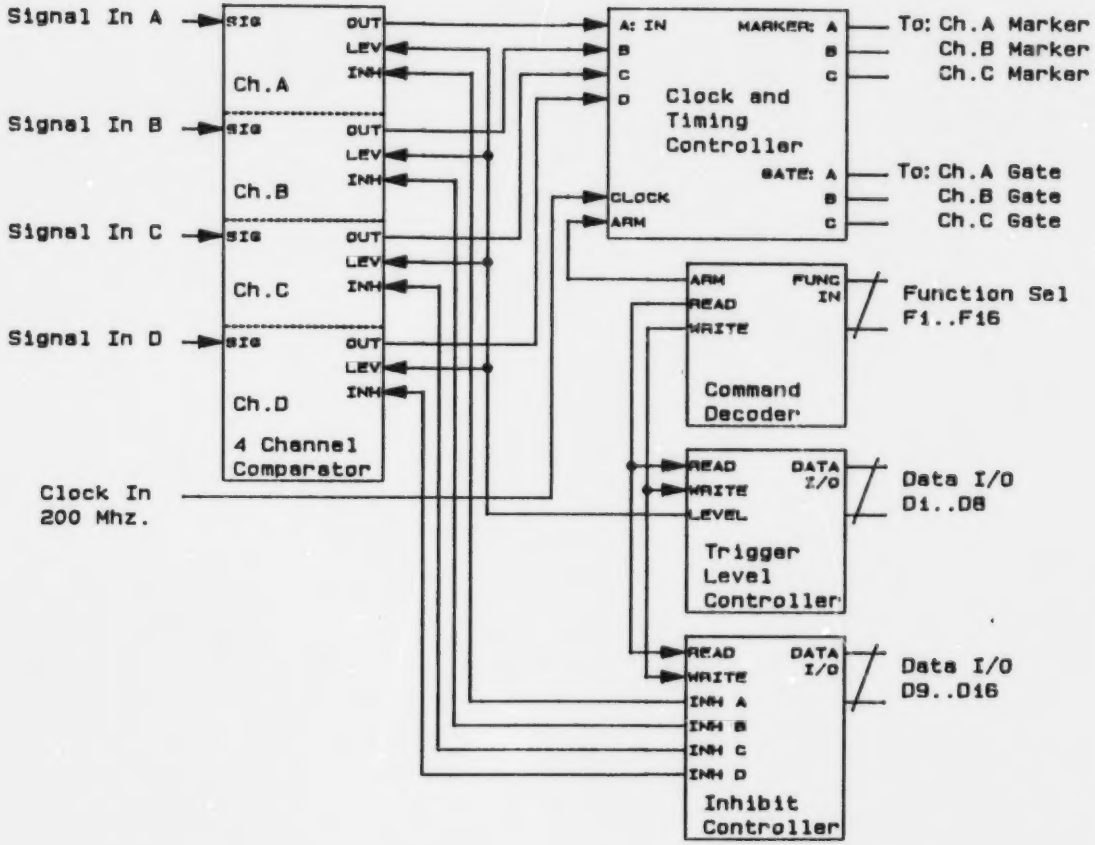
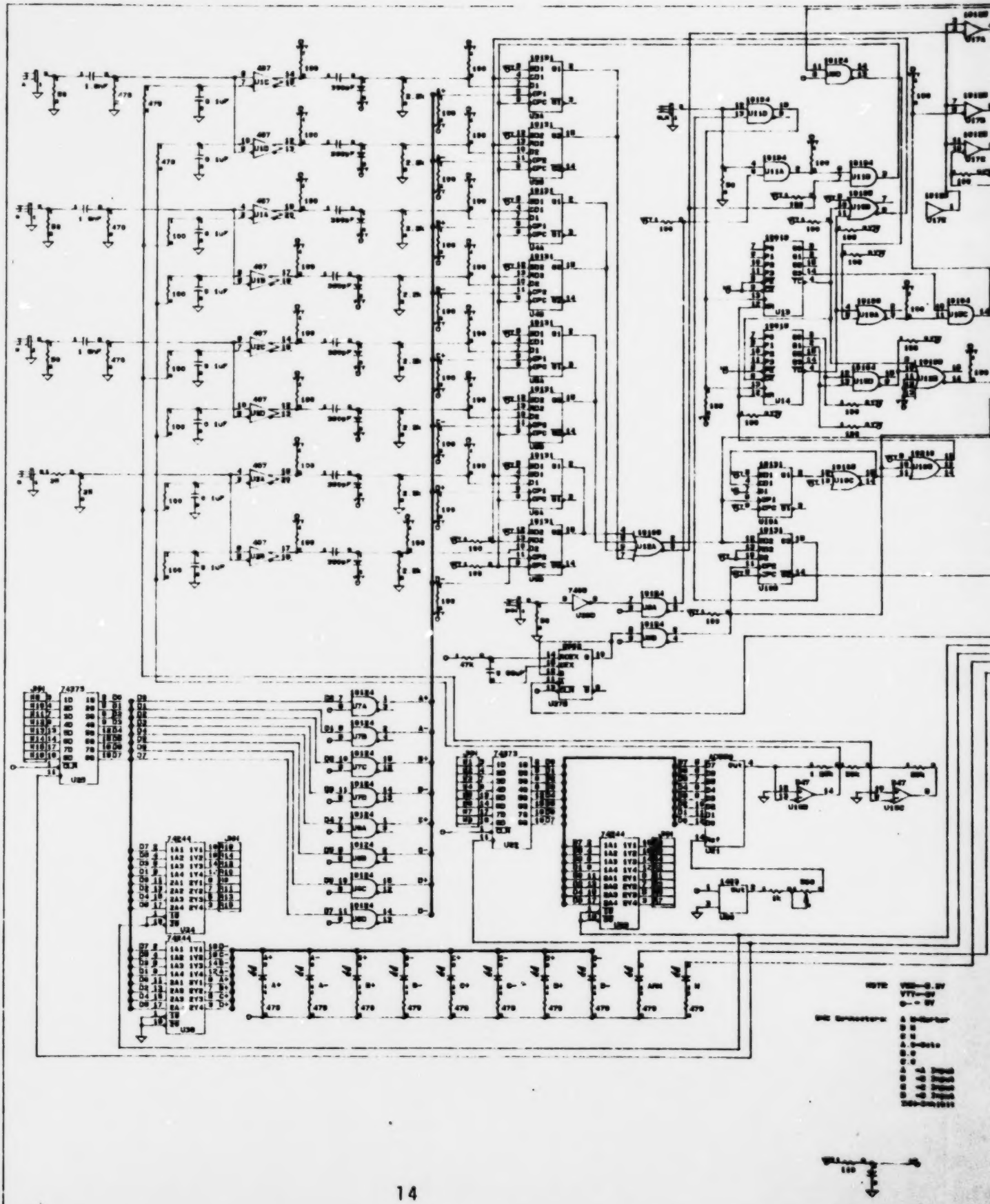


Figure 2

Trigger and Timing Controller
Circuit Block Diagram



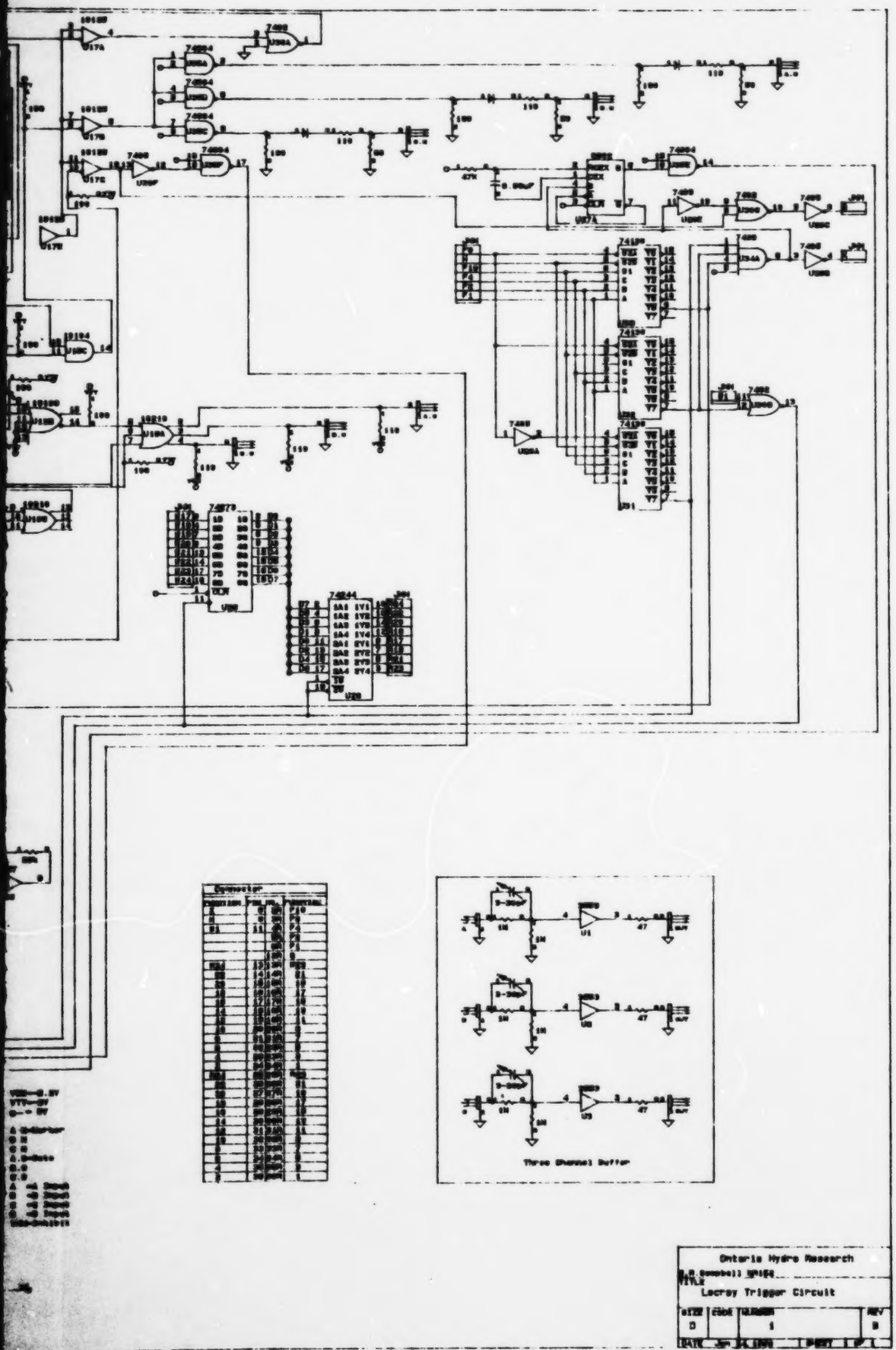


Figure 3
Circuit Diagram

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After the trigger circuit has been armed via a computer command, any signal meeting the trigger requirements in terms of magnitude and risetime will initiate a recording. Once a trigger is detected a gate pulse lasting 1.28 μs (256 samples) is sent to the digitizers, through the Clock and Timing Controller. After this first high speed recording, one gate pulse lasting 5 ns is sent to the digitizers every 1.28 μs. If another transient arrives meeting the trigger requirements, another gate pulse of 1.28 μs is sent to the digitizers. The gate pulses will then fall back to one 5 ns pulse every 1.28 μs until either another transient triggers the circuit or until the circuit is re-armed. Referring to the circuit diagram (Figure 3), the trigger level is set from the computer via a digital to analog converter in the Trigger Level Controller (IC's U19, U20, U21, U22, and U23). Each of the trigger states (positive on channel A, negative on channel A, positive on channel B, negative on channel B etc.) may be inhibited via the Inhibit Controller (IC's U7, U8, U24, U25, and U36) also under computer control. Under normal circumstances, triggering is enabled for either polarity for all 3 channels. The Four Channel Comparator (Figure 2) is made up of IC's U1 – U6 on the circuit diagram. The signal passes through a high pass filter (1.8 nF and 470 Ω, cutoff of about 1 μs) before being detected by the comparators. IC's U1 and U2 are quad high speed ECL comparators. A pair of comparators is used on each channel, one for positive and one for negative transitions. When one of the comparators triggers, the signal is latched by IC's U3, U4, U5 or U6. The outputs of the latches are OR'ed (U12A) and are used as the gate pulse, to reset the counter (U13 and U14) and to reset the ARM latch (U10B). The counter counts up until it reaches the terminal count of 255 at which time the comparator latches are reset and the gate pulse ends. The counters continue to count in a loop and on each terminal count a 5 nS gate pulse is sent to the digitizers (U15D, U12B and U16A). The counters continue until either another transient triggers the comparator latches or until an ARM pulse is received (U27B,U9B and U10B).

The trigger level is set by U19 – U23. An 8 bit number sent from the Computer is latched into U22 and converted to an analogue signal by U21. The trigger inhibit function is handled by U25. An 8 bit number is latched into U25 and each bit is used to disable or enable each of the comparator latches. The commands sent from the computer (read, write or arm) are decoded by U31 to U33. Commands from the computer are sent via an IEEE-488 interface, over the CAMAC crate backplane, to the trigger and timing circuit. Table 1 summarizes the commands accepted by the trigger and timing circuit.

An IBM compatible Compaq portable computer with 640 K RAM, a shock hardened 10 Mb hard disk, a real time clock, two printer ports, and an IEEE-488 interface port is used as a controller for the monitoring system. The computer is responsible for arming the digitizers and collecting and storing the data for future analysis.

For all valid Camac instructions the trigger and timing circuit will return a Q response. If the trigger circuit has been armed then an X response will also be returned. The trigger and timing circuit will recognize only the read, write, and arm commands and will not respond to any other commands.

TABLE 1
Camac control bytes for the
Trigger and Timing Circuit

BYTE	NAME	VALUE	ACTION
1	Flag	0	Read three bytes
		9	Arm the trigger circuit
		16	Write three bytes
2	Address	0	Always 0
3	Slot	1–21	Slot to address
4	Data	Any	Trigger Level 0 2.55 V 128 1.225 V 255 0 V
5	Data	Any	Trigger Control Register Bit Action Taken 7 Trigger on D – 6 Trigger on D + 5 Trigger on C – 4 Trigger on C + 3 Trigger on B – 2 Trigger on B + 1 Trigger on A – 0 Trigger on A +
6	Data	Any	Not Used

APPENDIX 2

Software Description

Appendix 2

Acquisition and Analysis Software

The data analysis and acquisition software was written in Microsoft Version 3.12 Fortran for a Compaq portable computer running under MSDOS version 2.0 or higher. The computer acts as a controller for the Lecroy digitizers and the trigger and timing circuit (TTC). Once the data has been acquired the additional software routines are used to analyze the captured data. The Fortran language is not ideal for this type of control application but was chosen because graphics and GPIB language interfaces were already available which could speed development time.

The graphics package used for display of the acquired data was HaloGraphics by Lifeboat Associates. This package provides standard plotting and scaling routines for a standard IBM compatible color display card. A National Instruments GPIB card and software drivers were used to interface to the Lecroy digitizers and TTC. The protocol used for controlling these devices is based on the Camac Crate Standard and is outlined in the hardware description (Appendix 1). Since Fortran does not provide a good interactive I/O environment, a group of assembler subroutines were written to handle keyboard scanning and disk I/O. These subroutines have been incorporated into a standard library called BLDOS-FOR which is described in Appendix 3.

The software is divided into two separate programs that share many common subroutines. The data acquisition program is called LECROY and is responsible for acquiring and storing the data. The analysis software is called DIAGnostics and is used to configure the default parameters for the LECROY program and to display and analyze the captured data.

Acquisition software (LECROY)

A listing for the LECROY program is given in Appendix 4. This program is used to acquire the surge data and store them on disk for future analysis. This program can be automatically loaded when the computer is turned on. Data collection continues until 30 events are recorded, after which the program terminates.

A flow chart of the main subroutines in the program is given in Figure 1. The mainline of the program first initializes the graphics buffers [initgraphics] then the GPIB port [setieee]. The default configuration for the digitizers and the timing and trigger circuit (TTC) is then loaded from disk [readdef]. After the configuration is sent to the digitizers and the TTC [setitup] the system is fully armed [armtrig] and ready to collect data. Once every second the program monitors the LAM line of the three digitizers [monitor] until they indicate a completed sampling condition. The data are then transferred to the computer [getdata] and stored on disk [writeit]. The captured data are plotted on the screen [plotit] and the digitizers rearmed. This cycle repeats until 30 events are recorded at which time the program terminates and returns to DOS.

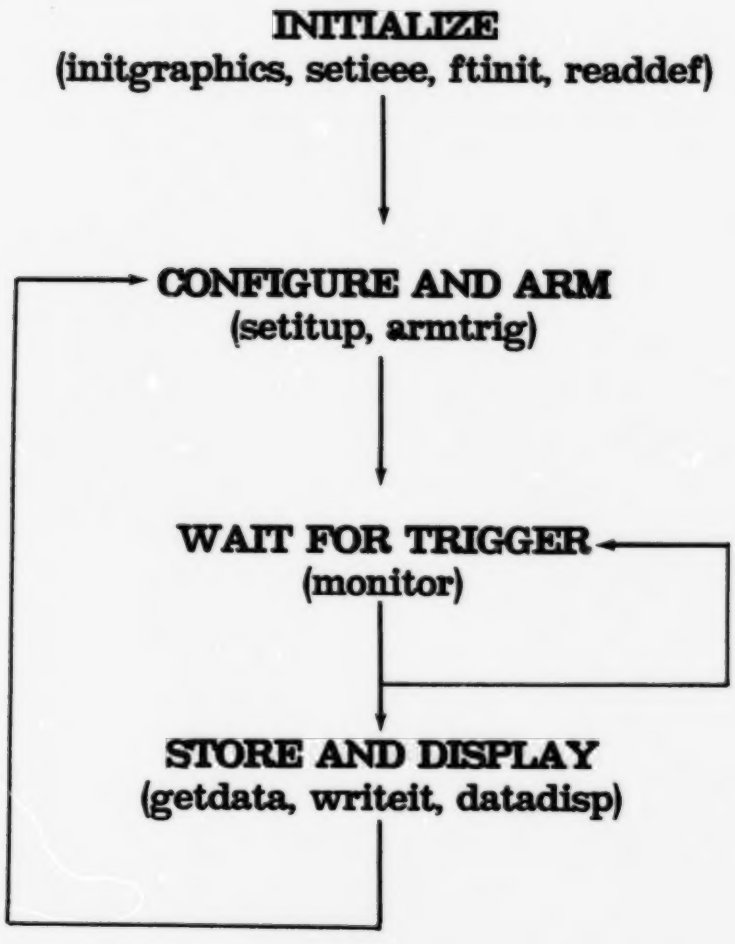

Figure 1
Flowchart For The LECROY Program

Although significant error checking is done by the program, no real error reporting scheme has been implemented. The program will do multiple retries of any failed function, report a general error to the screen, and continue to execute. Hooks have been placed in the code to allow for a more useful and informative error reporting scheme should such a scheme become necessary.

Analysis software (DIAG)

The data analysis software performs all the same functions as the LECROY program and also incorporates routines to display previously recorded data records. This menu driven program also allows the user to change the default hardware configuration used to setup the digitizers and the TTC. Listings for the subroutines used in DIAG that are not used in LECROY are given in Appendix 5.

The initial menu allows for a choice of 4 options; setup, display, diagnostics, exit. A user selects the appropriate option by moving the cursor using the cursor keys and pressing return over the desired option.

Setup:
The setup option displays another sub–menu which allows a user to specify such parameters as digitizer memory length, channel triggering characteristics, sampling speeds etc. After changing any of these parameters they can be saved to disk and will therefore become the new default parameters for both the DIAG and LECROY programs. A handy option in the setup also allows a user to scale the data from all 3 channels by a factor of 2, 3, or 4 times.

Display:
The display option prompts the user for a file number to be read in off disk. The drive specified in the default setup options will be used. The + and – keys are used to choose the file number. No error checking is done so an incorrectly specified disk drive or file number will result in the program terminating. After hitting return, the specified data file will be loaded and displayed on the screen. The ESC key can be used to return to the file selection menu.

A file may be displayed in 3 modes; normal mode, marker mode, or low resolution mode. When a file is first loaded the program defaults to the normal mode. Table 1 shows the keystrokes necessary to toggle between the three different modes

In the normal mode the cursor keys can be used to expand portions of the screen. A full list of commands available in this mode are given in table 2. The file number, location of the middle of the screen, and the number of high speed markers are also displayed in the top right–hand corner of the screen.

The marker mode displays the data one high speed marker at a time. Two cursors can be used in this mode to determine risetimes and magnitudes of surges. Although two cursors are available, only one will be displayed and can be moved at a time. A full list of the commands for this mode is given in table 3.

Since the time scale of the collected data is non–linear, a low resolution linear mode has been written that throws away the high speed portion of the data and plots the first 640 data bytes on a linear timescale. Although no accurate measurements can be done in this mode, it does allow the user to view the data in a more natural form. The commands for this mode are similar to those for the marker mode and are given in table 4.

Table 1
Mode selection commands

KEY	
D	redraw the screen and enter diagnostics mode
M	redraw the screen and enter marker mode
L	redraw the screen and enter low resolution mode

Table 2
Diagnostic mode commands

Diagnostics mode (D)

Cursors	define a window to be blown up
Return	redraws the portion of the data in the box
Home	redraws the data in the maximum dimensions
Tab	toggles the lock on the box movement
Esc	returns to the menu selections

Table 3
Marker mode commands

Marker mode (M)

+	goes to next marker
–	goes to previous marker
Cursors:	
Left/Right	moves half a page left or right
Up/Down	define a window to be blown up
PgUp	redraws data at marker in maximum dimensions
Home	move to first marker
End	move to last marker
Tab	toggles the lock on the box movements
Q	cursor1 left by 10
W	cursor1 left by 1
E	cursor1 right by 1
R	cursor1 right by 10

Table 3 continued

KEY	
U	cursor2 left by 10
I	cursor2 left by 1
O	cursor2 right by 1
P	cursor2 right by 10
T	toggle between a display of the absolute location of cursor1 and (cursor1 – cursor2) cursor1 – cursor2 locations
Esc	returns to the menu selections

Table 4
Low resolution mode commands

Low resolution mode (L)

Q	cursor1 left by 10
W	cursor1 left by 1
E	cursor1 right by 1
R	cursor1 right by 10
U	cursor2 left by 10
I	cursor2 left by 1
O	cursor2 right by 1
P	cursor2 right by 10
T	toggle between a display of the absolute location of cursor1 and (cursor1 – cursor2)
Esc	returns to the menu selections

Diagnostics:
The diagnostics option allows a user to set up the digitizers and the TTC in the same way it is done using the LECROY program. Once the data has been collected it will be displayed on the screen but will not be written to disk. By pressing ESC the user will be returned to the diagnostics menu from which the data can be saved on disk if required.

Exit:
When this option is selected the program terminates and returns control to DOS. Any changes made to the default setup that were not written to disk will be lost.

APPENDIX 3

BLDOSFOR utility programs

Software listings are on file in the Electrical Research Department

APPENDIX 4

Listings for LECROY program

Software listings are on file in the Electrical Research Department

APPENDIX 5

Listings for DIAG program

Software listings are on file in the Electrical Research Department